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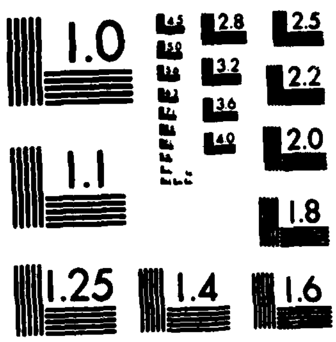


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RADIATION PRESSURE ON ATOMS:

LASER COOLING AND INTENSE FIELD EFFECTS

Progress Report

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At the present time we are awaiting the fabrication and delivery of the ring dye laser. In order that time not be wasted, and in order to provide initial testing of the apparatus we are preparing to carry out measurements of the transverse deflection of a sodium beam using a standing wave dye laser. The goal of these measurements and the experimental approach to be taken are described in the Appendix to this report.

We finally wish to comment that we recently initiated discussions with Dr. Dr. M. Ligare about joining the project.

## Experimental Progress

During the first six months of the project, our experimental efforts were concentrated on refurbishing the high-resolution alkali atomic beams apparatus at CCNY and on procuring the major components of the optical system required for the first stages of the cooling program. As of this date, the beam has been entirely reassembled and the high vacuum has been reestablished. An argon ion laser has also been procured, and an arrangement has been reached whereby Cooper Lasersonics will provide a ring dye laser capable of single mode operation at a scanning rate of 6 THz/s.

As a consequence of the 6 THz/s scan rate (a factor of four higher than originally envisioned) and the 10 MHz natural line width of the 3S-3P transition, it may be possible for the apparatus to be shortened appreciably for the optical pumping cycle. Although we are prepared to explore this option, we have nonetheless continued to base our experimental installation on the full beam path length of ~9 M.

During the last few months we have also learned that the state of the art for circular polarization has improved substantially. Specifically, if the sense of the polarization is held fixed, as is the case in our program, the use of a thermally isolated Soleil-Babinet compensator can provide circular polarizations as pure as 0.9999. If we are successful in duplicating this result, the problem of depopulation of the F=2 hyperfine ground substate during the cooling cycle will become moot. We have nonetheless taken the precaution of undertaking the design of a solenoid to provide an axial magnetic field of ~100 G along the beam line in order to increase the separation of the F'=3 and F'=2 excited substates, thereby easing the restrictions on the polarization substantially.

# Theoretical Progress

It is conventional to describe the motion of an atom in a laser field (and other D.C. fields) by a Fokker-Planck equation which is characterized by a force and a diffusion coefficient. The former is well understood but the latter still has some questions associated with it. Gordon and Askin have obtained a result for the diffusion coefficient in a spherically symmetric approximation. We have recently treated it as a second order tensor and have gotten a different result. The tensor has three terms. The leading term arises from the recoil of the atom during fluorescence, the second comes from gradients of the laser intensity and the D.C. fields and the last comes from a combination of the recoil term and gradients. The trace of our leading term agrees with the result of Gordon and Ashkin but there is no agreement at all with the other terms. The calculation was performed for a traveling wave laser and is being extended now to a standing wave laser by a graduate student.

The experiment being undertaken here will use a swept laser frequency to compensate for the change in resonance frequency (due to the Doppler effect) of the atom as it slows down. The other experiment in this field, by Philips et. al., used and uses a spatially varying Zeeman effect to accomplish the same thing. We are now investigating whether, and how, a combination of the two variations can make the slowing down process more efficient.

APPENDIX

Laser-Cooled and Trapped Atoms, (Proceedings of the Workshop on Spectroscopic Applications of Slow Atomic Beams, held at NBS, Gaithersburg, MD, 14-15 April 1983) Ed. by W. D. Phillips, Natl. Bur. Stand. (U. S.) Spec. Publ. 653 (1983).

# A Proposed Study of Photon Statistics in Fluorescence Through High Resolution Measurements of the Transverse Deflection of an Atomic Beam

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Information about the photon statistics in fluorescence can be obtained from the study of the variance in the angular deflection of a beam of atoms interacting with a transverse laser beam. The quantity of interest, $Q = (\overline{\Delta n^2} - \bar{n})/\bar{n}$, is a measure of the departure of the photon statistics from a Poisson distribution, where $\bar{n}$ is the mean and $\overline{\Delta n^2}$ is the variance of the number of photons emitted by a "two-level" atom. We demonstrate in this paper that our existing apparatus has sufficient resolution to make a statistically significant measurement of Q.

## 1. Introduction

The photon statistics associated with resonance fluorescence are of considerable fundamental interest and have been the subject of several recent papers.[1-7] In particular Mandel[1] has shown that it is possible for the statistics to be Poisson, sub-Poisson, or super-Poisson according to whether the variance, $\overline{\Delta n^2}$, of the number of emitted photons is respectively equal to, less than, or greater than $\bar{n}$, the mean of the number of photons emitted. For a two-level system, Mandel defined a parameter Q, given by

$$Q = \frac{\overline{\Delta n^2} - \bar{n}}{\bar{n}} \tag{1}$$

(which is a measure of the deviation of the statistics from a Poisson distribution) and showed, for example, that at resonance the value of Q should be $-3/4$. It is

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important that a measurement of Q be made to verify Mandel's predictions. A possible method of measuring Q, first suggested by Cook,[6] is the study of the deflection of a beam of atoms interacting with a transverse laser beam. To make a meaningful measurement of Q, however, requires a high resolution atomic beam apparatus. We propose to use such an apparatus already in existence to perform the measurement, and we will show in this paper that the apparatus has sufficient resolution to accomplish the task.

## 2. Proposed Experiment

The atom-laser beam geometry is shown in Figure 1. The deflection of the beam is due to absorption and a subsequent spontaneous re-emission of photons. As the

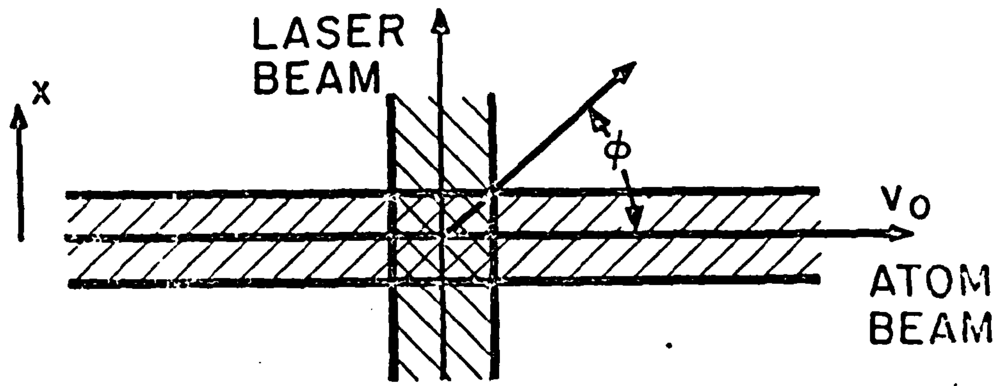


Figure 1. Atom-laser beam geometry.

atom travels through the laser field it absorbs photons and consequently recoils in the +x direction. If, in the time it takes to travel through the laser field the atom absorbs n photons it will acquire a transverse momentum equal to $(nh\nu/c)$, where h is Planck's constant, $\nu$ is the near-resonant laser frequency, and c is the speed of light. The n photons will be reradiated in a random direction, within the dipole distribution, adding a random component to the atom's momentum in the +x direction. The average angular deflection $\bar{\phi}$ of an atom of mass m initially travelling with a velocity $v_0$ is then given by

$$\bar{\phi} = \frac{nh\nu}{cmv_0} \tag{2}$$

for small $\bar{\phi}$. The variance in $\phi$ is due to both the statistical fluctuations in n and the randomness of the spontaneous decays. Thus for a monoenergetic beam of zero initial angular spread, the variance of the beam after interaction with the laser takes the form

$$\overline{\Delta\phi^2} = \left(\frac{h\nu}{cmv_0}\right)^2 \left(\overline{\Delta n^2} + \frac{2}{5}\bar{n}\right), \tag{3}$$

in which case Q can be expressed in terms of $\overline{\Delta\phi^2}$ and $\bar{\phi}$. However, in unfolding the experimental data, the initial angular dispersion and velocity distribution of the atom beam must be taken into account. Both of these quantities produce additional variances in $\phi$. Consequently Q can be expressed as

$$Q = \left(\frac{cmv_0}{h\nu}\right)\left(\frac{\overline{\Delta\phi^2} - \overline{\Delta\phi_0^2} - S^2\bar{\phi}^2}{\phi}\right) - \frac{7}{5}, \tag{4}$$

where $\overline{\Delta\phi_0^2}$ is the angular dispersion in the initial beam and $S^2\bar{\phi}^2$ is due to the velocity distribution in the beam. If the velocity spread is small, S can be written as $S \approx 2\Delta v/v_0$. For an accurate measurement of Q both $\overline{\Delta\phi_0^2}$ and $S^2\bar{\phi}^2$ must be small compared to $\overline{\Delta\phi^2}$. These conditions will be satisfied if

$$\overline{\Delta\phi_0^2} < \left(\frac{h\nu}{mcv_0}\right)^2 \bar{n} \tag{5}$$

and

$$\frac{\Delta v}{v_0} < \frac{1}{2\bar{n}^{1/2}}. \tag{6}$$

For example, if n = 100, Eqs. (5) and (6) yield the requirements

$(\overline{\Delta\phi_0^2})^{1/2} < 3 \times 10^{-4}$ rad and $v/v_0 < 1/20$. Both of these requirements can be satisfied with our present apparatus.

In addition to satisfying the requirements expressed by Eqs. (5) and (6), the atom beam must be prepared as a two-state system. For sodium, all the experimental conditions can be met in a spatially narrow, velocity-selected beam prepared in the $F = 2$, $m_F = 2$ hyperfine ground state. If the state-selected sodium beam intersects a circularly polarized laser beam tuned to the transition $3^2S_{1/2}(F=2, m_F=2)$ to $3^2P_{3/2}(F=3, m_F=3)$, a two-state approximation can be used since the laser field will cause the atom to oscillate between the $(F=2, m_F=2)$ and $(F=3, m_F=3)$ states until a spontaneous decay occurs with such a decay returning the atom to the initial $(F=2, m_F=2)$ ground state.

The velocity and state selection can be accomplished as shown in Figure 2. The offset source together with the inhomogeneous magnetic field and system of slits serve as a velocity selector.[9] It can be shown that for the given dimensions and with the magnet operating in the high-field region, the range of velocities in the beam exiting from slit $S_3$ will be given by $(\Delta v/v_0) \approx (s_0/d)$, where $s_0$ is the width of the source slit and d is the displacement of the source slit from the beam axis. A ratio of 1/50 is easily attainable. The state selection is accomplished by the use of the E-H gradient magnet.[8] This magnet, operated in the low-field region, is adjusted such that the state of interest $(F=2, m_F=2)$ passes through undeflected. For this state the magnetic force is balanced by the electric force while for other hyperfine states angular deflections will occur that will prevent them from passing through slits $S_2$ and $S_3$. The arrangement shown in Figure 2 therefore will provide a beam in the $(F=2, m_F=2)$ hyperfine state with the required range of velocities. The angular divergence of the beam at the interaction region for the given dimensions will be less than $4 \times 10^{-5}$ rad, well within the required range of values.

A scale drawing of the apparatus is shown in Figure 3, with a surface-barrier (hot-wire) atom detector (labeled I) located 130 cm downstream from the interaction region (labeled G). For the given geometry the intensity of the beam arriving at the detector can be estimated easily. Assuming that the source is operated at a vapor pressure of $10^{-1}$ Torr and that the dimensions of all slits are $25\ \mu m \times 2.5$ mm, $\sim 10^8$ atoms/cm$^2$s will arrive on the beam axis at the plane of the detector with the desired velocity distribution and state selection. This corresponds to $\sim 2 \times 10^{-14}$ A leaving the hot-wire detector. With the use of an electron multiplier having a gain of $10^5$, the final detector current will be $\sim 2 \times 10^{-9}$ A, about ten times greater than the background noise. Furthermore, if the laser beam is modulated and phase sensitive detection, employed, recoil currents

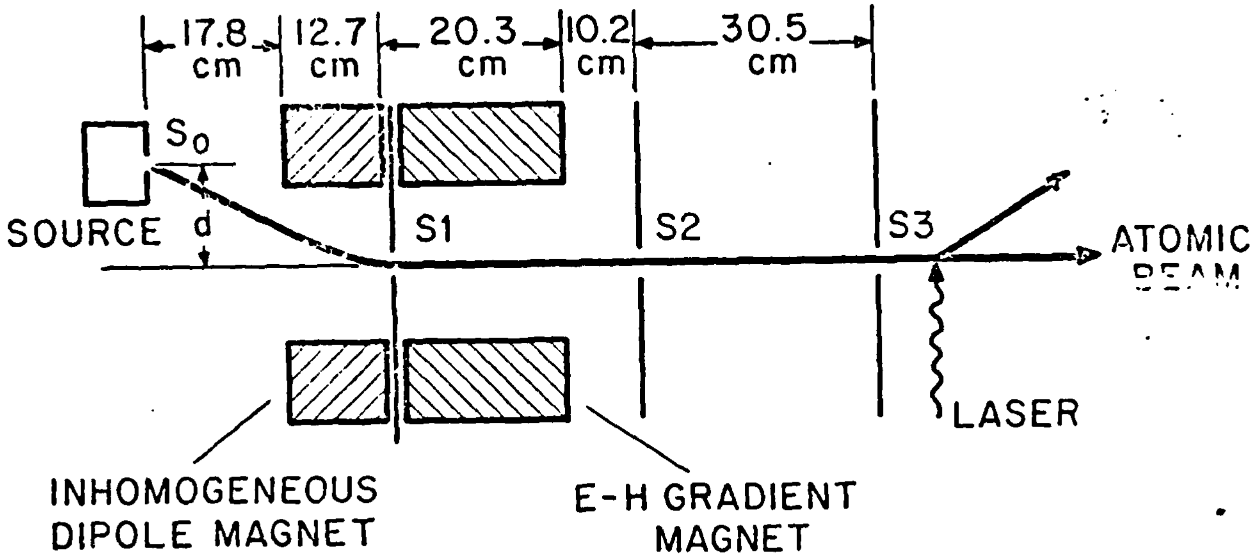


Figure 2. Schematic diagram of experiment showing the inhomogeneous dipole-magnet velocity selector and the E-H gradient magnet[8] state selector. The slits, $S_0$, $S_1$, $S_2$, and $S_3$ are all taken to have dimensions 25 $\mu$m x 2.5 mm.

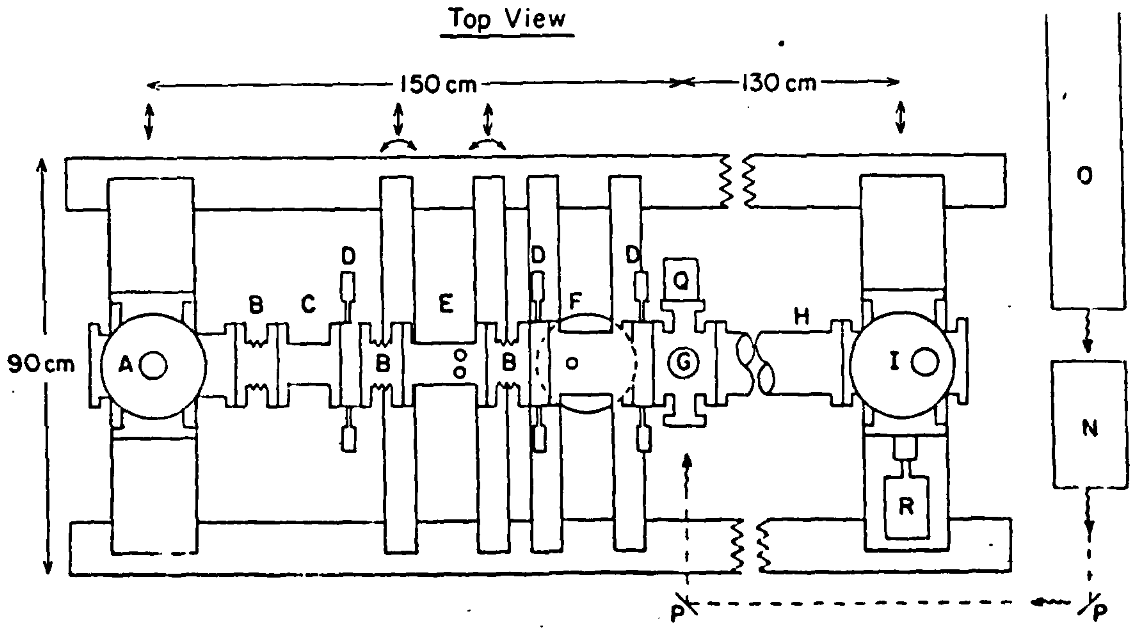


Figure 3. Scale drawing of apparatus showing atom source, A; bellows, B; velocity selector, C; adjustable slits, D; E-H gradient magnet, E; beam flag, F; interaction region, G; drift space, H; surface barrier atom detector, I; dye laser, N; argon ion laser, O; mirror, P; power metter, Q; and stepping motor, R.

that are less than 1/100 of the initial beam can be measured. Thus the beam intensity should be quite sufficient for the proposed measurements.

If the atom beam detector has a transverse resolution of 25 μm, the measurements can be carried out with an angular resolution of $2 \times 10^{-5}$ rad. Now if the distribution is Poisson, the angular variance will be given by

$$\Delta\phi^2 = \left(\frac{h\nu}{cmv_0}\right)^2 \left(\frac{7}{5}\bar{n}\right) . \tag{7}$$

Assuming a laser operating single mode with a power output of ~50 mW (more than sufficient to saturate the transition) and a beam width of ~2.5 mm, an atom will scatter ~100 photons in passing through the laser beam. Therefore from Eqs. 2, 3 and 6, for a Poisson distribution, $\bar{\phi}$ will be $\sim 10^{-3}$ rad and $(\overline{\Delta\phi^2})^{1/2}$ will be $\sim 4 \times 10^{-4}$ rad. Both of these quantities should be readily observable. Thus deviations from the Poisson character should be measurable, and Mandel's formulation should be eminently amenable to test.

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